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CARBON FOOTPRINTING

Life cycle carbon footprint measurement of Portland cement and ready mix concrete for a city with local scarcity of resources like Hong Kong

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Abstract
Purpose The construction sector was the second largest contributor of Hong Kong carbon emissions, and 85 % of the emission from construction was external in nature. The carbon footprint embodied in each building construction material varies considerably under different conditions. This study aims to quantify the embodied carbon footprint of building construction materials used in Hong Kong with the consideration of local factors and to investigate how the region-specific characteristic would affect the result.
Methods A "cradle-to-site" system boundary was used, including raw material extraction, manufacturing, and transport until the material reaches the construction site. Data were collected from manufacturers in local and nearby regions. Portland cement and ready mix concrete were selected as examples in this study to demonstrate the calculation.
Results and discussion It is indicated that for cement, decomposition of limestone contributes the largest to the total greenhouse gas emission over the life cycle, followed by fuel combustion. The surveyed cement plant performs at an average level in manufacture, but the import of raw materials increases the total emissions. For concrete, the major contributor is cement manufacturing. Comparison with other databases reveals that there is room for improvement in carbon reduction of the surveyed plants. The "cradle-to-site" results on cement and concrete show no significant difference from the "cradle-to-gate" results.
Conclusions Hong Kong's dependency on imports increases the carbon footprint of locally used building construction materials. The presented methodology can be modified and extended to other materials, thereby helping lower the carbon footprint of construction activities by providing a benchmark for selecting green materials.

Keywords Carbon footprint · Life cycle · Portland cement · Ready mix concrete

1 Introduction

In recent years, climate change and global warming issues have attracted increasing concern around the world. The Intergovernmental Panel on Climate Change (IPCC) states that anthropogenic greenhouse gas (GHG) emission is the major cause of global warming phenomenon (Pachauri and Reisinger 2007). In response to demands for sustainable development, industry has a responsibility to lower energy consumption and GHG emission over the manufacturing life cycle. Within the industrial sector as a whole, construction activities account for much of the energy consumption and carbon emissions. According to the WWF's Hong Kong Ecological Footprint Report 2010, in 2007 the construction sector contributed the second largest carbon footprint in Hong Kong, of which 85 % was embodied in imported goods and services (Cornish et al. 2011). In addition to direct emissions from the construction sector, this footprint includes emissions from all upstream material inputs to the construction activities.

This study aims to quantify the embodied carbon footprint of building construction materials used in Hong Kong with the consideration of local factors (i.e., resource scarcity, few manufacturers, and dependency on imported goods) and to investigate how the region-specific characteristic would affect the result. After reviewing various carbon footprint calculation methodologies for building construction materials, a modified methodology framework has been applied concerning the

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impact from regional factors, with the intention to develop a carbon inventory of the building construction materials commonly used in Hong Kong. The results of this study will help lower the carbon footprint of the construction industry in Hong Kong by providing a benchmark for the selection of green materials.

This paper describes our methodology framework and illustrates the steps to be taken in life cycle carbon measurement of building construction materials. Among various building materials, Portland cement attracts much more attention not only because of its huge production and consumption worldwide but also because of the large volumes of CO_2 emitted in the manufacture of Portland cement clinker. Concrete, made mainly by Portland cement, is the most widely used material. Currently, there is no practical alternative to concrete for many modern construction projects, so the construction industry has to pay attention to minimizing the overall CO_2 emissions associated with concrete construction to the greatest extent in a cost-effective way (Gartner 2004). Clearly, Portland cement and concrete are of high importance to the sustainable development of the construction industry due to their wide application as well as significant impact to the environment. Thus, Portland cement and ready mix concrete were selected as examples in this study in order to demonstrate the methodology framework, which can serve as a reference for the study of other types of building construction materials. Similar life cycle inventory (LCI) or life cycle impact assessment (LCIA) studies on cement and concrete or other building materials have been carried out in other regions or countries, evaluating the potential impacts (e.g., global warming, resource depletion, land use and transformation, etc.) of the product systems brought to the environment (Josa et al. 2007; Chen et al. 2010; Liu et al. 2010a, b). However, most of such studies focus on "cradle-to-gate" life cycle, and some data were obtained from secondary sources (Josa et al. 2004, 2007; Flower and Sanjayan 2007; Hammond and Jones 2008; Chen et al. 2010; Van den Heede and De Belie 2012). Regarding the level of technology used and the geographical setting of the factory, such LCI analysis should be more region-specific to represent the local conditions (Liu et al. 2010a). Since Hong Kong is a trading city with large amounts of imported upstream materials, transportation of the imported goods may affect more to the total impact during the whole life cycle. The demand for cement in Hong Kong has remained between 2.8 and 3 million tpa over the past few years. With the fast infrastructure development, it is expected that the consumption of cement in Hong Kong has an annual growth of 5 % approximately (Gupta and Hopper 2013). Even though Hong Kong has very little manufacturing industries due to its resource scarcity, it does have local cement manufacturing with cement grinding and clinker production lines. According to the Hong Kong Merchandise Trade Statistics—Imports report and the Hong Kong Annual Digest of Statistics report published by the Hong Kong Census and Statistics Department (HKCSD), Fig. 1 presents the cement supply distribution of the Hong Kong market in the recent 5 years (2008 to 2012) (HKCSD 2008a, b, 2009a, b, 2010a, b, 2011a, b, 2012a, b). The locally manufactured cement accounted for 51 % of the total supply. For the imported cement, mainland China and Japan were the two major supplying regions occupying about 90 % of the Hong Kong imported cement market. Taiwan supplied cement to Hong Kong with 3 % market share. As for ready mix concrete, they are all locally manufactured. The freshly made concrete is mixed during the transport stage to the construction site. However, due to the limited resources, the major raw materials of making concrete, such as cement and aggregate, need to be imported from other regions. Based on the concept of life cycle assessment (LCA) and with reference to the ISO 14040 standard, the system boundary of this study is set as "cradle-to-site", which evaluates the life cycle environmental impact (i.e., carbon footprint) of building construction materials from the stages of raw materials extraction, raw material transport to the manufacturing plant, product manufacture, and transport of product until it has reached the construction site (Hammond and Jones 2008; ISO 2006).

2 Methodology

2.1 Framework

The framework of this study is shown in Fig. 2. To develop a region-specific inventory, the manufacturing processes for cement and concrete in local and nearby areas were studied, the GHG emission sources over the specified life cycle were identified, and the standard GHG emission calculation guidelines were reviewed. Based on the information obtained from the background study cited, detailed system boundaries describing the manufacturing processes from "cradle-to-site" were determined for cement and concrete, respectively. Questionnaires specific to local and nearby manufacturers were then designed and distributed, with the aim to collect first-hand data. This data collection stage was the key to the whole study because the availability, quality, and completeness of the data could influence the accuracy and reliability of the final results. In the data collection work, iterative review and revision of the questionnaires can be conducted in response to the feedbacks from industry. GHG emissions of the building construction materials were then calculated with reference to the relevant guidelines and standards. Finally, the results were analyzed, compared, and reported, which summarized the whole study.

2.2 System boundary

This section presents the "cradle-to-site" life cycle system boundaries for Portland cement and ready mix concrete in this study.

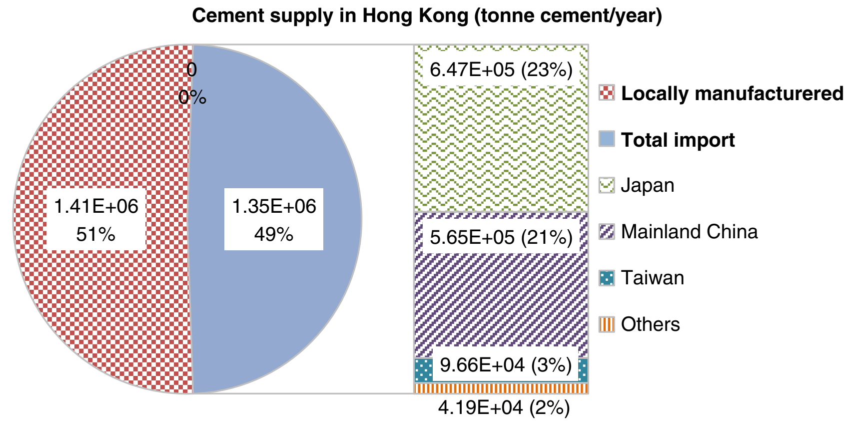


Fig. 1 Cement supply distribution of Hong Kong market

The type of Portland cement studied in this paper is type I Portland cement (CEM I, EN197-1: 2000). As shown in Fig. 3, the "cradle" of the system boundary for Portland cement refers to the extraction and quarrying of the typical raw materials, which are limestone, clay, sand, iron ore, and gypsum (CSI 2011a, b; Zhang 2011). Sandstone and iron ore tailing are used in some plants to replace sand and iron ore, respectively. The raw materials are transported to manufacturing plants and then separately ground to fine powder and mixed. Calcination, a combustion process that consumes fuel, is then performed. Due to the chemical reaction of the carbonates at a high temperature of 1,400 to 1,500 °C, CO_2 is directly emitted during calcination and clinker is produced (Duggal 1998; Zhang 2011; Li et al. 2011). The ash from fuels is absorbed into the clinker matrix. During the production of clinker, limestone, which is mainly calcium carbonate ($CaCO_3$), is heated, or calcined, producing lime and CO_2 (Hanle et al. 2006).

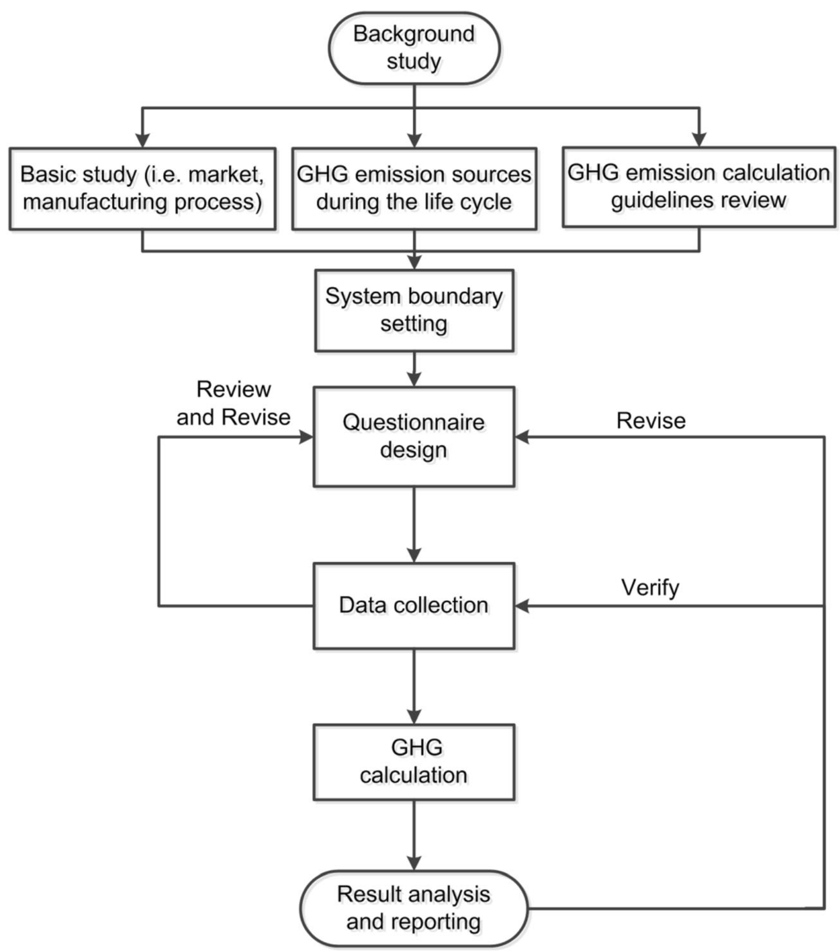


Fig. 2 The methodology framework of this study

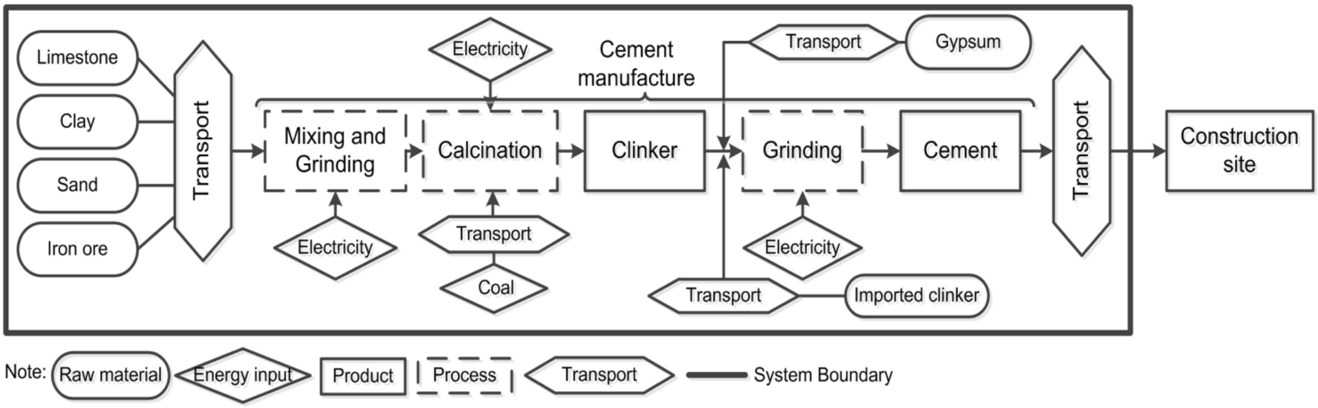


Fig. 3 System boundary of Portland cement

In some factories, self-manufactured clinker cannot satisfy the demand for cement production, so clinker may be imported from other manufacturers. The GHG emissions from the production and transport of imported clinker are included in our system boundary for cement. After clinker preparation, gypsum is added for regulating the setting time of cement. Then, the final grinding process produces the cement product. The last phase in the system boundary is the transport of the cement products. As shown in Fig. 3, electricity and coal are the energy inputs during the cement manufacture process and account for GHG emissions.

All direct and indirect GHG emissions associated with each phase shown in Fig. 3 are covered in this study. They are (1) the GHG emissions generated from each upstream material extraction and production process, (2) the GHG emissions from the transport of upstream materials, fuels, imported clinker, and products, and (3) the GHG emissions during the cement manufacture process at factory (i.e., calcination, fuel combustion, electricity consumption, and imported clinker).

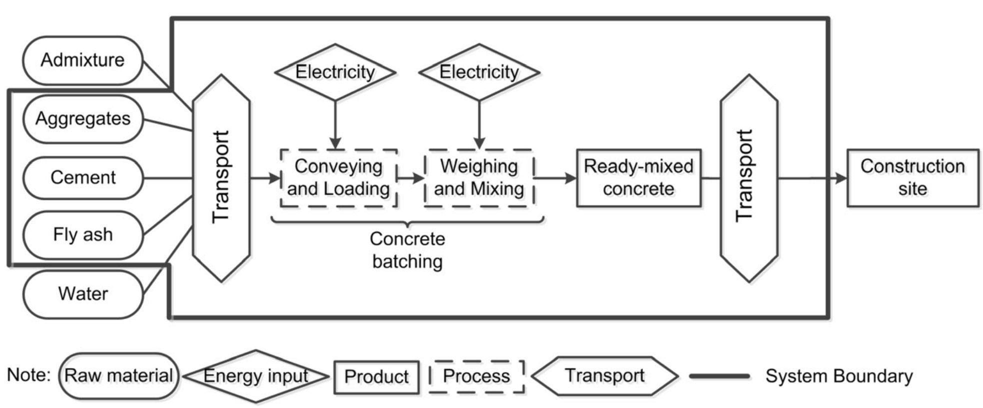
Figure 4 shows the "cradle-to-site" life cycle system boundary of ready mix concrete. The raw materials include admixture, aggregates, cement, fly ash, and water (Nawy 2004). After being transported to concrete batching plants, the raw materials are conveyed and loaded into silos for storage in the plants. The raw materials are then weighed in specific ratios for mixing. After mixing, the fresh ready mix concrete is transferred to construction sites using mixing trucks. Electricity is the energy input during the batching process.

The GHG emissions for concrete were calculated using the methods similar to those used for Portland cement. However, the "cradle" of the system boundary for concrete does not cover the extraction and production of admixture and water because the admixture production and water used have an insignificant impact on the total GHG emission according to Flower and Sanjayan (2007).

2.3 Questionnaire design and data collection

Based on the information obtained from the background study and the literature review, a set of bilingual questionnaires (in English and Traditional Chinese) for cement and ready mix concrete manufacturers was developed. Following the system boundaries described earlier, the main body of the questionnaires covers three major parts: (1) raw materials extraction and production, (2) consumption of fuels and electricity, and (3) transport of upstream materials, fuels, and products (i.e., raw materials to manufacturing plant and products to consumer or construction site).

Fig. 4 System boundary of ready mix concrete



To collect first-hand information about the locally used cement and concrete products, bilingual questionnaires were distributed to the manufacturers in Hong Kong and nearby regions (e.g., Macau, Southern China, etc.) that supply cement and concrete products to the Hong Kong market. For illustrative purposes, this paper shows the examples from one of the cement manufacturers and one of the ready mix concrete manufacturers. As requested, the manufacturers' names and the information sources are kept anonymous due to confidentiality. Some information and numbers are also hidden or slightly modified due to confidentiality. The modified raw material quantities, production data, and transport information for the cement and concrete illustrative examples are summarized in Tables 1 and 2.

As shown in Tables 1 and 2, compared to the concrete production example, the cement production example involves more materials imported from overseas regions such as Japan and Vietnam, resulting in longer transport distances. However, the concrete production example involves more types of transport means. Both transport distances and transport means types are considered in the GHG emission calculation.

3 Results for Portland cement and concrete

The results of our GHG emission calculation are expressed in terms of carbon dioxide equivalent (CO_2-e), which refers to the global warming potential (GWP) with respect to one unit of carbon dioxide. Expressing all GHG emissions in terms of CO_2-e allows the different greenhouse gases to be grouped together (B.C. MoE 2013). Usually, the six greenhouse gases identified in Kyoto Protocol are considered when measuring GHG emissions in terms of CO_2-e. They are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), per-fluorocarbons (PFCs), and sulfur hexafluoride (SF_6). In this study, the three major ones (CO_2, CH_4, and N_2O) among the six were considered in calculation. According to IPCC Second Assessment Report (SAR), the GWP values of the three gases are 1 (CO_2), 21 (CH_4), and 310 (N_2O) (Houghton et al. 1995).

3.1 Results of CO_2-e for Portland cement

The GHG emission calculation for Portland cement over its "cradle-to-site" life cycle consists of three parts: (1) extraction and production of upstream materials (raw materials and fuel), (2) cement manufacture at factory, and (3) transport of upstream materials and products.

3.1.1 Upstream materials for Portland cement

For each upstream material, the emission factors in terms of different greenhouse gases are summarized in Table 3. However, the associated emission from gypsum production was excluded in this calculation since the gypsum used in the surveyed cement plant is a by-product of the desulfurization process in the nearby power plant. To ensure that the results were region-specific, local data were selected as much as possible. For some data which could not be obtained from local sources, average values based on a global range from widely recognized inventories were adopted. The emission factors in terms of CO_2-e per kilogram of upstream material were calculated based on the GWP values. As shown in the last column of Table 3, the CO_2-e value of coal is almost four

Table 1 Basic information of the cement manufacturing factory example illustrated in this study (raw materials, fuel and electricity consumption, production, and transport)

	Quantity (t/year)	Location	Distance (km)	Transport type
Material				
Limestone	416,000	Guangdong, China (source)	250[a]	Inland shipping
	624,000	South Japan (source)	3,202[b]	Ocean shipping
Sand	130,000	Guangdong, China (source)	250[a]	Inland shipping
Clay	104,000	Guangdong, China (source)	250[a]	Inland shipping
Iron ore	26,000	South Japan (source)	3,202[b]	Ocean shipping
Gypsum	90,000	Hong Kong (source)	0[c]	Truck
Imported clinker	100,000	Vietnam (source)	1,764[b]	Ocean shipping
Energy				
Coal	237,900 (t/year)	Indonesia (source)	3,555[b]	Ocean shipping
Electricity	87 (kW h/t clinker)	NA	NA	Local grid
	135 (kW h/t cement)	NA	NA	Local grid
Product				
Clinker	1,300,000	NA	NA	NA
Cement	1,500,000	Concrete batching plants within HK (location)	100 km	Barge
			100 km	Truck

[a] Estimated

[b] JEMAI 2012

[c] Assumed to be zero because the source location is close to the plant

Table 2 Basic information for the ready mix concrete batching plant illustrated in this study (raw materials, production, and transport)

	Quantity	Source location	Diesel oil (L/yr)	Distance (km)	Transport type
Raw material					
Cement	265,000 t/year	Hong Kong		Variable[a]	Tanker/pipeline/barge
	265,000 t/year	Yingde, China		300	Truck
Aggregate	1,250,000 t/year	Hong Kong		Variable[a]	Truck/conveyor/barge
	1,250,000 t/year	Dongguan, China		129	Truck
Fly ash	99,000 t/year	Hong Kong		Variable[a]	Tanker/barge
Admixture	6,486 t/year	Hong Kong		Variable[a]	Truck
Product					
Ready mix concrete	1,300,000 m^3/year		300,000	NA	Truck

[a] Local distance within Hong Kong is variable due to different locations of batching plants, which range from 3 to 48 km

times the CO_2 value, indicating the significant impact of CH_4 emission during coal mining.

3.1.2 Cement manufacture

As presented in Fig. 3, GHG emissions are mainly from the chemical reaction in calcination and the associated energy inputs (coal combustion and electricity consumption). Table 4 shows the emission factors for each process of clinker and cement production. For calcination, the CO_2 emission factor value was obtained based on the first-hand data provided by the factory with reference to the IPCC Guideline (Hanle et al. 2006) and the Cement Sustainability Initiative (CSI) standard (CSI 2011a, b). It is not required to quantify the non-CO_2 GHG emissions from kiln as the emissions of CH_4 from cement kilns are minimal due to the high combustion temperatures in the kiln. Likewise, the data compiled by the CSI Task Force indicate that the emissions of N_2O from cement kiln are typically small (CSI 2011a, b). According to the factory, the consumption of coal is 3.6×10^{-3} GJ/kg clinker. Emission factors for coal combustion were obtained from the Energy sector of the IPCC Guideline (Gómez et al. 2006). Electricity used in cement plants can come from local grid and from internal waste heat recovery (WHR) generation. Currently, the application of WHR generation technology in cement manufacture is increasingly common worldwide, especially in Asian countries such as China, India, Japan, and Pakistan (Khattak et al. 2012; Harder 2013). However, the surveyed plant in this paper does not generate power by applying the WHR system. The external electricity consumption for clinker and cement are 87 kW h/t clinker and 135 kW h/t cement, respectively. The CO_2-e emission factor for electricity consumption refers to the local power plant which supplies power to the surveyed cement factory. In cement production, GHG emissions from imported clinker should be considered. According to the CSI Standard, the embodied carbon of imported clinker is 0.865 kg CO_2-e/kg imported clinker (CSI 2011a, b). Referring to the annual coal consumption amount and annual production quantities shown in Table 1, the GHG emissions during the cement manufacture process were calculated as 0.950 kg CO_2-e per kilogram of clinker produced and 0.917 kg CO_2-e per kilogram of cement produced.

Table 3 Emission factors of the upstream materials of Portland cement

Upstream material	kg CO_2/kg material	kg CH_4 fossil/ kg material	kg N_2O/kg material	kg CO_2-e/kg material
Limestone	4.83×10^{-3}	1.71×10^{-5}	6.78×10^{-7}	5.39×10^{-3}[a]
	NA	NA	NA	4.11×10^{-3}[b]
Sand	2.63×10^{-3}	7.60×10^{-6}	3.99×10^{-8}	2.80×10^{-3}[c]
Clay	2.31×10^{-3}	1.33×10^{-5}	2.15×10^{-8}	2.59×10^{-3}[d]
Iron ore	4.29×10^{-3}	4.06×10^{-6}	0	4.38×10^{-3}[e]
Coal	2.56×10^{-2}	3.06×10^{-3}	0	8.98×10^{-2}[f]

[a] CLCD 2009

[b] JEMAI 2011

[c] CLCD 2011

[d] CLCD 2008

[e] Ecoinvent 2007

[f] Ecoinvent 2010

3.1.3 Transport for Portland cement

As shown in Table 1, inland shipping and ocean shipping are the two major transport types for raw materials in the illustrative example. The inland shipping distance from Guangdong Province of mainland China to the factory was estimated, and the ocean shipping distances from Southern Japan, Vietnam, and Indonesia to the factory were extracted from a Japanese database which provides the travel distances among major ports in the world (JEMAI 2012). The emission factor for inland shipping in China was obtained from a Chinese LCI database (CLCD 2010), while the emission factor for international marine shipping was obtained from World Resources Institute (WRI 2011). After unit conversion, Table 5 presents the transport emission factors in SI units.

Table 4 Emission factors for the Portland cement manufacture

	kg CO_2/unit	kg CH_4/unit	kg N_2O/unit	kg CO_2-e /unit
Clinker				
Calcination	0.551	0	0	0.551 kg/kg clinker
Coal	96 kg/GJ	0.01 kg/GJ	0.0015 kg/GJ	96.68 kg/GJ[a]
Electricity	NA	NA	NA	0.59 kg/kW h[b]
CO_2-e/kg clinker, 0.950				
Cement				
Calcination	0.478	0	0	0.478 kg/kg cement
Coal	96 kg/GJ	0.01 kg/GJ	0.0015 kg/GJ	96.68 kg/GJ[a]
Electricity	NA	NA	NA	0.59 kg/kW h[b]
Imported clinker	0.865	0	0	0.865 kg/kg imported clinker[c]
CO_2-e/kg cement, 0.917				

[a] Gómez et al. 2006
[b] Provided by electricity supplier
[c] CSI 2011a, b

The factory delivers cement products by barge and by truck with an estimated travel distance of 100 km. The emission factors of barge delivery were obtained from WRI (2011). The emission factors of diesel oil truck delivery were obtained from the Hong Kong Environmental Protection Department (HKEPD 2010a, b) and the Electrical and Mechanical Services Department (EMSD 2013).

3.1.4 Summary and discussion for Portland cement results

After determination of the emission factors for each part, the CO_2-e calculation per unit of clinker and cement could be calculated. By multiplying the quantities shown in Table 1 by the CO_2-e emission factors for each material or each process, the total CO_2-e emissions were calculated. The GHG emissions in terms of per unit were then calculated by dividing the total CO_2-e emissions by the clinker production quantity and the cement production quantity. Table 6 and Fig. 5 present the final results and percentage distribution of each part, which clearly indicate that the cement manufacture part accounts for most of the GHG emissions over the "cradle-to-site" life cycle of Portland cement. The bar chart in Fig. 5 shows that in the cement manufacture part, calcination is the largest contributor, followed by coal combustion. Transport accounts for 7 % of the total emissions, which is a relative high contribution because in other studies transport only contributed around 3 % of total impact (Josa et al. 2004; Chen et al. 2010; Jiang and Wang 2010). In the perspective of transport, upstream material transport has over 95 % of the impact because the surveyed plant supplies products to the nearby regions (including Hong Kong market) but imports raw materials from overseas.

Since China is the largest consumer and producer of cement products, the associated CO_2 emission is also a big concern for the Chinese cement industry. In response to the targets of energy saving and emission reduction as announced by the government, the China Building Materials Academy (CBMA) investigated the CO_2 emissions (fuel-derived CO_2 and raw materials CO_2) from cement manufacturing process from 42 large- and medium-sized cement manufacturing enterprises from mainland China (CBMA 2011a). To evaluate the level of the surveyed plant's performance based on the benchmark of the whole Chinese industry, a result comparison between this study and the CBMA's study was made. Table 7 presents the key values (i.e., highest, lowest, median, mean) from the CBMA study report (CBMA 2011a) and compares the data with the results of this paper. The comparison clearly shows that the performance of the surveyed plant is around the

Table 5 Emission factors for the transport of upstream materials and products

	Fuel type	kg CO_2	kg CH_4	kg N_2O	kg CO_2-e
Water transport					
Inland shipping	Diesel oil	1.25×10^{-2} t km	5.97×10^{-5} t km	6.16×10^{-7} t km	1.39×10^{-2} t km[a]
Ocean shipping	Heavy fuel oil	3.29×10^{-2} t km	2.81×10^{-6} t km	9.60×10^{-7} t km	3.33×10^{-2} t km[b]
Road transport					
Truck/tanker	Diesel oil	2.614 L	1.45×10^{-4} L	7.20×10^{-5} L	2.64 L[c]

[a] CLCD 2010
[b] WRI 2011
[c] HKEPD 2010a, b; EMSD 2013

Table 6 Results of CO_2-e for each part of Portland cement life cycle

	kg CO_2-e/kg clinker	kg CO_2-e/kg cement
Upstream material		
Limestone	3.699×10^{-3}	3.206×10^{-3}
Sand	2.800×10^{-4}	2.427×10^{-4}
Clay	2.075×10^{-4}	1.798×10^{-4}
Iron ore	8.751×10^{-5}	7.584×10^{-5}
Coal	1.644×10^{-2}	1.424×10^{-2}
Total CO_2-e	2.071×10^{-2}	1.795×10^{-2}
Cement manufacture		
Calcination	0.551	0.478
Coal combustion	0.348	0.302
Electricity consumption	0.051	0.080
Imported clinker	NA	0.058
Total CO_2-e	0.950	0.917
Transport		
Limestone	5.223×10^{-2}	4.527×10^{-2}
Sand	3.486×10^{-4}	3.021×10^{-4}
Clay	2.789×10^{-4}	2.417×10^{-4}
Iron ore	2.130×10^{-3}	1.846×10^{-3}
Imported clinker	4.472×10^{-3}	3.877×10^{-3}
Coal	2.163×10^{-2}	1.875×10^{-2}
Cement	3.770×10^{-3}	3.267×10^{-3}
Total CO_2-e	8.486×10^{-2}	7.355×10^{-2}
Overall total CO_2-e emission	1.056	1.008

average level of the 42 mainland China enterprises in the CBMA study. As shown in Table 7, the GHG emissions per unit of cement and that of clinker are both comparable to the mean values of the mainland China enterprises. However, for the energy consumption per unit of clinker, this study is 19 % larger than that of CBMA study, which indicates that the electricity consumption (135 kW h/t cement and 87 kW h/t clinker) in the surveyed plant is higher than that of Chinese enterprises. Indeed another report from CBMA (CBMA 2011b) provided the electricity consumption data of the 42 Chinese enterprises, which are 95 kW h/t cement and 71 kW h/t clinker on average, respectively (see Table 7). According to the Chinese National Standard, "the norm of energy consumption per unit product of cement" (GB16780-2007), the upper limit of electricity consumption for the cement plant (with cement capacity of 4,000 t/day or above) is 105 kW h/t, indicating that the electricity consumption of the surveyed plant is far beyond the standard (SAC 2007). From this comparison, it is reasonable to consider that the surveyed plant ranks at the medium level in terms of performance on calcination and combustion, but there is much room to be improved to reach the high level of the Chinese industry since the electricity consumption is still a big concern.

Besides the comparison with the CBMA study, the results of this paper were compared with other existing databases from other regions, including Inventory of Carbon & Energy (ICE), Chinese reference Life Cycle Database (CLCD), Japan Carbon Footprint of Products (CFP) Database, and Korea Life Cycle Inventory (LCI) Database. For other existing databases, the system boundary is "cradle-to-gate" (KEITI 2002; JEMAI 2010a, b; Liu et al. 2010b; Hammond and Jones 2011). In other words, our "cradle-to-site" system boundary in this study has a broader coverage than the others and includes the GHG emissions from transport of products which the other databases exclude. In order to make a fair comparison, the results of this study were converted to "cradle-to-gate" values by deducting the emissions of product transport from the previous "cradle-to-site" calculation. Table 8 presents the system boundary of each database as well as the detailed values for concrete and cement. This section only discusses the comparison on cement (the 2nd column) because the discussion on concrete comparison will be presented in the following subsection. As shown in Table 8, the result of this study is the largest among the other databases, followed by ICE. The Chinese large-scale plants using new dry process technology emit the least emissions, which is probably due to the application of advanced technology as well as the Chinese industry's increasing effort on energy saving and emission reduction actions throughout the recent years. Indeed the result for the surveyed plant in this paper does not perform

Fig. 5 GHG emission distribution of each part for Portland cement (kg CO_2-e/kg cement)

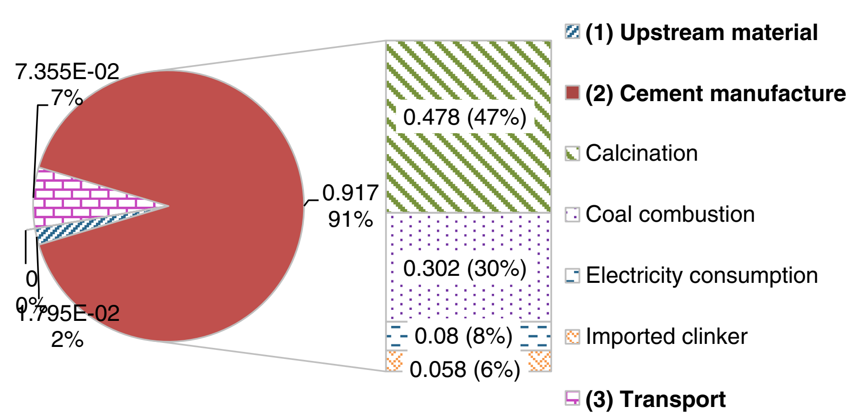


Table 7 Results comparison between the surveyed cement plant and enterprises from mainland China (CBMA 2011a, b)

Comparison item	Highest	Lowest	Median	Mean	Results in this study
kg CO_2/kg cement	0.921	0.330	0.815	0.752	0.777[a]
kg CO_2/kg clinker	0.953	0.825	0.863	0.870	0.897[a]
GJ/t clinker	4.211	2.885	3.355	3.369	4.161[b]
kW h/t cement	108	80	95	95	135
kW h/ t clinker	79	59	71	71	87

[a] Converted from CO_2-e values in Table 6 by deducting the associated CH_4 and N_2O results, representing only the CO_2 emission in calcination and fuel combustion

[b] Obtained by adding the energy consumption from coal combustion (3.6 GJ/t clinker) and total electricity consumption (135 kW h/t cement, equivalent to 0.561 GJ/t clinker)

much worse than the average level of the Chinese enterprises according to a previous comparison with the CBMA study, whereas the embodied carbon in upstream materials and transport increases the total result.

To reduce the large amount of CO_2 and decrease the global warming impact of cement manufacture in a more effective way, actions could be taken focusing on the clinker production system where calcination and combustion occur. It would be good to introduce advanced technology and equipment to enhance the efficiency of calcination and reduce energy consumption. For instance, the new dry process production line which increases the production capacity but reduces the energy consumption at the same time could be applied. To reduce the carbon emission from burning of coal, other low-carbon fossil fuels or alternative fuels could be used. Other improvements in manufacturing are better maintenance and upgrade of equipment (e.g., clinker cooler, preheater) as well as reasonable process control and management, which may help increase the efficiency and decrease the electricity consumption. Another energy-saving strategy would be the adoption of the previously mentioned WHR system, which could supply up to 30 % of the electrical power requirement of a cement plant depending on the applied technology (Harder 2013). In addition, using alternative raw materials (e.g., slag or fly ash) could help reduce carbonate input, thereby decreasing the CO_2 output from carbonate (Worrell et al. 2001). Besides the actions in the kiln system and raw material selection, transport of upstream material is another concern. Even though performing at an average level in the cement manufacturing process, the overall GHG emission at "cradle-to-site" life cycle increases with the large amount of imported raw materials. The surveyed plant could consider adjusting the supply chain of raw materials and importing more raw materials from nearby regions like Southern China instead of overseas countries. However, the change of source locations may cause the change of transport mode from shipping to road transport, which may still keep high GHG emissions since truck transport normally releases larger emissions than ship (HKEPD 2010a, b; WRI 2011). Furthermore, recycling of wastes or by-products to raw materials would be another good option.

Table 8 Results of comparison of CO_2-e with other existing databases

Database	kg CO_2-e/kg cement	kg CO_2-e/kg concrete	kg CO_2-e/m^3 concrete	System boundary
ICE	0.950[a]	0.1810[b]	425.35[c]	Cradle to gate
CLCD	0.768[d]	ND	321.63[e]	Cradle to gate
Japan CFP database	0.882[f]	ND	346[g]	Cradle to gate
Korea LCI database	0.944[h]	ND	346[i]	Cradle to gate
This study	1.005	0.1805	424.28	Cradle to gate
This study	1.008	0.1808	424.89	Cradle to site

Values only represent CO_2 emission

[a] Average CEM I Portland cement

[b] 400 kg CEM I/m^3 concrete

[c] Back-calculated based on concrete density of 2,350 kg/m^3 (Hammond and Jones 2011)

[d] Chinese market average level of cement produced by large-scale (>4,000 t/day clinker) dry process technology (CLCD 2010)

[e] C30 concrete (CLCD 2008)

[f] Portland cement

[g] Ready mix concrete (JEMAI 2012)

[h] Portland cement type 1 (KEITI 2002)

[i] Ready mix concrete (KEITI 2008)

3.2 Results of CO_2-e for ready mix concrete

Similar to the study and calculation for Portland cement, this section presents the calculation of GHG emissions in terms of CO_2-e for ready mix concrete. The calculation consists of three parts: (1) extraction and production of upstream materials, (2) concrete batching at plants, and (3) transport of upstream materials and products.

3.2.1 Upstream materials for ready mix concrete

As discussed earlier in "Results for Portland cement and concrete", only three types of raw materials for ready mix concrete were included in the system boundary in this study. Embodied carbon for cement (1.005 kg CO_2-e/kg cement) referred to the previous calculation for Portland cement, as shown in Table 6. Emission factor of aggregate (3.07×10^{-3} kg CO_2-e/kg aggregate) was extracted from a report provided by the surveyed concrete batching plants. As for fly ash, since no local data was available, the emission factor (4.00×10^{-3} kg CO_2-e/kg fly ash) was obtained from a report published by Mineral Products Association (2011).

3.2.2 Concrete batching

The concrete batching process only consumes electricity as the energy input and is relatively simple compared to the cement manufacture process. According to the surveyed plants, electricity at the plants is provided by two suppliers. One supplier accounts for 98 % of the electricity supply with a total annual consumption of 3,300,000 kW h, whereas the other supplier accounts for the remaining 2 %. The emission factors of the first and the second electricity suppliers are 0.59 and 0.81 kg CO_2-e/kW h, respectively.

3.2.3 Transport for ready mix concrete

As indicated in Table 2, cement and aggregate are either imported from mainland China or bought from local suppliers. As for the cement bought from a local source, it is transported by pipeline if the batching plants are close to the raw material suppliers and transported by truck or tanker to other batching plants which are far away from suppliers. The emission factor of pipeline transport is 0.005 kg CO_2-e/t km, as suggested by McKinnon and Piecyk (2010). Similar to cement, aggregates are transported by conveyor for the batching plants near the local quarry site. In this case, GHG emissions due to conveyor transport are included in the electricity consumption. Barge delivery is needed when the supplier or batching plant is located on an island. The emission factor of barge delivery is 0.033 kg CO_2-e/t km, referring to the emission factor of ocean shipping (see Table 5). The emission factor of concrete road transport (i.e., raw material from mainland China/Hong Kong, product delivery within Hong Kong) is the same as that of cement product road transport (HKEPD 2010a, b; EMSD 2013), as shown in Table 5.

3.2.4 Summary and discussion for ready mix concrete results

Applying the emission factors determined in the cited three parts, the total GHG emission was calculated. To obtain the CO_2-e value per unit weight of concrete, the density of the ready mix concrete was assumed as 2,350 kg/m^3 concrete (Hammond and Jones 2011). Table 9 summarizes the final calculation results for each part in terms of kg CO_2-e/m^3 concrete and kg CO_2-e/kg concrete. As indicated in Table 9, the part of upstream material extraction and processing contributes the majority of the total GHG emission because cement as raw material has a rather high embodied carbon value. In addition, the results for raw material transport are separately presented in terms of the source location. Obviously, longer distance transport increases the associated emissions as compared to local transport. However, there are very few locally manufactured materials in Hong Kong, and Hong Kong often has limited options for source location of material resources. For example, there are currently two local quarries in Hong Kong, one of which is scheduled to end its operation in 2 years by 2015. Therefore, the aggregate supply in Hong Kong will be more dependent on the imports from mainland China (HKEPD 2010a, b; CEDD 2011). The findings indicate that for reduction of carbon footprint of concrete, the most effective way is to select alternative cementitious materials (e.g., GGBFS, silica fume, fly ash) for the replacement of the high-carbon Portland cement. However, the performance of final concrete products should also be paid attention to when considering the replacement of cement. As cement plays an important role for hydration of concrete, the different ratios of Portland cement and supplementary cementitious materials may influence the strength and durability of concrete. Furthermore, state specifications of using supplementary cementitious materials for concrete are limited currently; thus, the industry stakeholders are more cautious when considering the replacement (Toutanji et al. 2004; Owaid et al. 2012).

Table 9 Results of CO_2-e for each part of ready mix concrete life cycle

	kg CO_2-e/m^3 concrete	kg CO_2-e/kg concrete
Upstream material		
Cement	409.73	0.1744
Aggregate	5.90	0.0025
Fly ash	0.30	0.0001
Total CO_2-e	415.94 [a]	0.1770[a]
Concrete batching		
Electricity supplier 1	1.47	6.2457×10^{-4} [b]
Electricity supplier 2	0.04	1.7499×10^{-5} [b]
Total CO_2-e	1.51	0.0006
Transport		
Raw materials within HK	0.94	3.9856×10^{-4}
Raw materials from mainland	5.89	2.5037×10^{-3}
Products transport	0.61	0.0003
Total CO_2-e	7.44	0.0032
Total CO_2-e emission	424.89	0.1808

[a] Figures may not add up to total due to rounding off

The results for concrete were also compared with other existing databases as shown in Table 8. For most of the databases, the GHG emissions per unit of concrete are much smaller than that in this study. This is because for other databases, the values on the raw material (i.e., cement) are smaller than those in this study. However, there is an exception for ICE. The result for cement presented in this study is larger than the ICE value, whereas the result for concrete presented in this study is smaller than the ICE value, probably because the concrete plants surveyed in this study add fly ash as cement replacement in the batching process to reduce the amount of cement necessary for each unit volume of concrete. However, the concrete type “400 kg CEM I/m^3 concrete” in ICE does not include the addition of fly ash.

4 Conclusions

Local scarcity of resources in Hong Kong makes the city largely dependent on import of construction materials, thus making the construction sector's external carbon emissions contribution as high as 85 % of the total carbon footprint accounted for the construction industry, as reported by WWF in 2011 (Cornish et al. 2011). This paper presents and illustrates the methodology framework for measuring the life cycle carbon emissions of locally used building construction materials in Hong Kong. A “cradle-to-site” life cycle system boundary was used in this study, covering the “cradle-to-gate” life cycle stages plus the transport stage of imported materials. To illustrate the steps of GHG emission calculation, Portland cement and ready mix concrete were selected as examples in this paper. The results show that calcination and coal combustion are the major sources of GHG emissions for cement over its “cradle-to-site” life cycle, whereas the high embodied carbon emission in cement manufacture is the largest contributor to GHG emission for ready mix concrete over its “cradle-to-site” life cycle. The results were then compared with the values provided in other studies and existing databases in other regions. The comparison reveals that the results in this study are larger than most of other databases, and therefore there is much room for improvement in carbon reduction of the surveyed plants. The comparison on cement indicates that the surveyed cement plant performs at an average level in terms of clinker calcination and combustion, whereas the electricity consumption is rather high as compared to Chinese plants. In addition, the dependency on import of raw materials increases the total emissions over the life cycle. With the consideration of import of materials, this study extended the system boundary to “cradle-to-site” to include the transport of materials from plant to the construction site. However, the “cradle-to-site” results on cement and concrete presented in this paper do not show a significant difference from the “cradle-to-gate” results. This is because the surveyed plants supply products to local or nearby markets, which makes the distance of the transport very short and the associated results smaller. With such findings, it could not be concluded that the impact of transport from plant to site is insignificant for all the construction materials used in Hong Kong. In fact, there are many other commonly used materials (e.g., steel, plywood) which are manufactured in remote regions and countries and then imported to Hong Kong through long-distance trip. The authors suggest that the results would be different if the study is extended to investigate the “cradle-to-site” carbon footprint of other materials.

As the values of embodied carbon are region specific, this study aims to collect first-hand data in Hong Kong and nearby regions, wherever possible, for accuracy and reliability of the final results. However, when the information from the manufacturers was limited, the second-hand information from existing databases or literature would be used. In addition, some assumptions were made for the manufacturing and transport calculation due to the limited information. The methodology framework presented in this paper can be applied to building construction materials other than cement and concrete. In the near future, the scope of this study will be extended to more building construction materials, and a building material carbon inventory database will be developed for the Hong Kong market. Such a database could help build a low-carbon-built environment in Hong Kong by providing a benchmark for selection of green construction materials and a basis for prediction of carbon emission in building infrastructures.

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